VALIDATION OF THE PARAMETERIZED REAL-TIME IONOSPHERIC SPECIFICATION MODEL (PRISM) VERSION 1.6B USING TOPEX TOTAL ELECTRON CONTENT (TEC) DATA

THESIS

R. David Coxwell, Captain, USAF

AFIT/GAP/ENP/96D-05

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GAP/ENP/96D-05

VALIDATION OF THE PARAMETERIZED REAL-TIME IONOSPHERIC SPECIFICATION MODEL (PRISM) VERSION 1.6B USING TOPEX TOTAL ELECTRON CONTENT (TEC) DATA

THESIS

R. David Coxwell, Captain, USAF

AFIT/GAP/ENP/96D-05

“The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.”

AFIT/GAP/ENP/96D-05

VALIDATION OF THE PARAMETERIZED REAL-TIME IONOSPHERIC SPECIFICATION MODEL (PRISM) VERSION 1.6B USING TOPEX TOTAL ELECTRON CONTENT (TEC) DATA

THESIS

Presented to the Faculty of the Graduate School of Engineering

of the Air Force Institute of Technology

Air Education and Training Command in Partial Fulfillment of the

Requirements for the Degree of Master of Science

R. David Coxwell, B.S.

Captain, USAF

December 1996

AFIT/GAP/ENP/96D-05

VALIDATION OF THE PARAMETERIZED REAL-TIME

IONOSPHERIC SPECIFICATION MODEL (PRISM)

VERSION 1.6B USING TOPEX TOTAL ELECTRON

CONTENT (TEC) DATA

R. David Coxwell, B.S.
Captain, USAF

Approved:

Derrill T. Goldizen Chairman, Advisory Committee	25 Nov 96
David E. Weeks Member, Advisory Committee	25 Nov 96
Gerald C. Gerace Member, Advisory Committee	25 Nov 96

Preface

The ultimate objective of this work was to provide a thorough validation of the Parameterized Real-Time Ionospheric Specification Model (PRISM) Version 1.6b that tests PRISM's accuracy in the operational environment. The majority of my time, however, was not occupied analyzing various runs of PRISM. I spent much of my time writing computer codes, coordinating data collection, and processing data. This extensive preparation resulted in my needing assistance from a large list of people.

I start by acknowledging the assistance of my thesis advisor, Major Derrill Goldizen, and my thesis committee members, Dr. David Weeks and Major Gerald Gerace. Major Goldizen provided constant support and advice while, at the same time, not imposing upon me his vision of the direction this thesis should have been headed. This allowed me the freedom to make changes in the methodology as I felt the situation required. I congratulate Dr. Weeks and Major Gerace on their determination to sift through my meandering text and provide constructive criticism.

Dr. Dave Anderson, Pat Doherty and Terry Bullett of Phillips Laboratories, Hanscom AFB, were very generous with their time and energy. They provided advice, resources and insight that saved me a tremendous amount of time that would have otherwise been spent in additional research. Special thanks to Pat Doherty, who was so involved with my work that she may as well have been on my thesis committee. Without her help, my thesis would have been much more difficult to complete. Other Phillips Lab personnel provided much of the data that I used. Thanks to Virginia Ewell and Jane Vladimer for their efforts processing TOPEX data, Paul Gendron for processing GPS

data, Peter Sultan and Fred Rich for providing DMSP data and information, and Greg Bishop for providing information on IMS. The time they saved me in data processing helped make this thesis possible.

Lincoln Brown and Rob Daniell of CPI were extraordinarily patient in handling what probably seemed to be an inexhaustible number of questions related to the PRISM code. Had Lincoln not provided assistance, I would probably still be trying to compile the PRISM code.

Other individuals who have my gratitude: Daniel Melendez at NRL; Karen O'Loughlin at NGDC; Bob Prochaska and Vern Patterson at Hughes STX; SSgt Ted Payton, Gary White and Capt Clark Groves at 50^{th} WS; Capt Rick Davila at Air Weather Service; Tony Manucci and Tom Lockhart at NASA/JPL; Bodo Reinisch at the University of Massachusetts at Lowell.

The computer resources were provided by the Atmospheric Physics Weather Lab at AFIT, under the management of MSgt Pete Rahe. MSgt Rahe made every effort to assist me and answered all questions I had concerning the UNIX operating system. He has my sincerest gratitude. Thanks also to Major Tuell, Major Dungey and Lt Col Walters who eagerly answered questions on a variety of subjects.

On a more personal level, I must thank my parents, Caroline and James Murphy. They raised me, fed me, and provided shelter through my graduation from college. Had they not provided this assistance, and a healthy amount of moral guidance, I would not have been in a position to pursue a graduate degree of any sort.

Finally, I must humbly acknowledge my dependence upon Jesus for the strength that allowed me to finish this 18 month adventure in frustration.

R. David Coxwell

Table of Contents

List of Figures

List of Tables

VALIDATION OF THE PARAMETERIZED REAL-TIME IONOSPHERIC SPECIFICATION MODEL (PRISM) VERSION 1.6B USING TOPEX TOTAL ELECTRON CONTENT (TEC) DATA

Abstract

The ability of the most recent version of PRISM (1.6b) to accurately specify real-time TEC values was validated against "ground truth" TEC data obtained by the Ocean TOPography EXperiment (TOPEX). PRISM "driver" data came from two sources: the ground-based Digital Ionospheric Sounding System (DISS - critical frequencies and layer heights) and the International Global Positioning System (GPS) Service for Geodynamics (IGS GPS - TEC values). The TEC "ground truth" data were obtained by the NASA dual-frequency radar altimeter on-board the TOPEX satellite during 1995. 950 TEC estimates obtained from PRISM 1.6b were compared with corresponding values observed by the TOPEX satellite along multiple orbital tracks. Comparison points were chosen to be representative of different seasons (Equinox, Summer, and Winter), local times (0000L, 0600L, 1200L, and 1800L), and latitudes (30° N and equatorial). The results of PRISM-TOPEX chi-square goodness-of-fit calculations are presented to quantify the accuracy of PRISM across seasons, local times, latitudes, and varying subsets of input data.

VALIDATION OF THE PARAMETERIZED REAL-TIME IONOSPHERIC SPECIFICATION MODEL (PRISM) VERSION 1.6B USING TOPEX TOTAL ELECTRON CONTENT (TEC) DATA

1. INTRODUCTION

The Parameterized Real-Time Ionospheric Specification Model (PRISM) was developed by Computational Physics, Incorporated, (CPI) for use by the Air Force Space Forecast Center (AFSFC), also known as the 50th Weather Squadron (50th WS). PRISM's purpose is to provide an accurate real-time ionospheric specification for DoD use. The phrase "ionospheric specification" refers to the PRISM output, which literally specifies the state of the ionosphere globally or regionally at a given time in terms of electron density profile parameters (f_oF2, h_mF2, TEC, etc.), actual electron density profiles, or both. An accurate specification of the ionosphere is necessary for initialization of the first DoD ionospheric forecast model currently being developed.

Once a specification model is developed, its output could be used to optimize the operation of many systems. Examples include forecasting the effectiveness of satellite communications and High Frequency (HF) radiowave propagation. Most DoD organizations use either satellite or HF radio communications or both. It is therefore imperative that these organizations have some source of guidance as to when ionospheric conditions are expected to be optimal for these modes of communication. More

importantly, these organizations need to know when communications will be impaired by ionospheric conditions. An accurate specification of the ionosphere is a necessary tool if effective forecasts of satellite and HF radiowave propagation conditions are to be possible. In addition, PRISM output can be used to aid in post-event analysis so that the causes of operational problems can be identified as either the result of ionospheric conditions or system problems. Examples of events which would require analysis include spontaneous satellite circuit switching, electrostatic discharges resulting in satellite damage and single event upsets or "bit flips". All of these events result from satellite interaction with the space environment, so any analysis would require knowledge of the satellite's environment before the exact cause of an event could be determined.

PRISM is designed to provide hourly ionospheric specifications in near real-time, and it does this using a variety of model-run-time input data such as electron density profile parameters (f_oF2, h_mF2, f_oE, and h_mE) from the Digital Ionospheric Sounding System (DISS), Total Electron Content (TEC) measurements from the Ionospheric Monitoring System (IMS), *in situ* plasma measurements from the Defense Meteorological Satellite Program (DMSP), vertical TEC measurements from the International GPS Service for Geodynamics (IGS), the daily and 90-day average $F_{10.7}$ flux (10.7 radio wave emissions), and real-time planetary geomagnetic index (K_p) data.

The scope of this thesis will be limited to validating the ability of PRISM to produce values for TEC, the height-integrated sum of electrons contained within a vertical column of $1m^2$ cross-section, that are in agreement with measurements obtained from the NASA dual-frequency radar altimeter on board the Ocean TOPography

EXperiment (TOPEX) satellite, a platform designed to collect information about the world's oceans. Specifically, TOPEX measures the height of the sea surface in order to study the dynamics of the circulation of the world's oceans, ultimately leading to improved understanding of the ocean's role in global climate change [*Fu et al.*, 1994]. A series of estimates by PRISM will be compared with the corresponding values observed by the TOPEX satellite along multiple orbital tracks. These orbital tracks will be strategically selected so that they coincide with regions not only of abundant data, but also with regions of sparse data. Then, the results will be statistically analyzed to measure PRISM's accuracy.

1.1 Previous Validation of PRISM

There has been only one previous validation of PRISM, that validation having been conducted by CPI in 1994 on PRISM version 1.2. PRISM output was compared with output from the Ionospheric Conductivity and Electron Density (ICED) model, and both sets were then validated against a collection of representative "ground truth" stations [*Daniell et al., 1994*]. A summary of the results is given in Table 1. One TEC unit is

Table 1. Summary of PRISM and ICED Validation Results [*Daniell et al.*, 1994]

Quantity	ICED	PRISM	Improvement Over ICED
RMS TEC error (TEC Units)	7.1	3.1	56%
RMS TEC error (%)	31%	8%	74%

defined as 10^{16} electrons/meter^2, and ionospheric values for TEC can range from 0 to over 100 TEC units, depending upon the time of day, solar conditions, geographic location and

satellite altitude [*Callahan*, 1984]. PRISM obviously provides a significant improvement over ICED. The important fact to note here, though, is that there is some question as to the representativeness of the data used in the first validation. In fact, one of the conclusions made by CPI was that further validation was necessary since their efforts were hampered by difficulties in obtaining a complete set of historical data sufficient for validation purposes. For the purposes of this validation, a complete set of data for input into PRISM is not paramount, nor even desired. The data set used for input is to be representative of the real-time data that is currently used by 50th WS on a day-to-day basis. This will allow this validation to be representative of the performance of PRISM in the operational environment.

1.2 PRISM and Its Components

PRISM is a real-time ionospheric specification model which combines output from a parameterized climatological database with real-time observations using a Real-Time Adjustment (RTA), or "weighting", algorithm (see Figure 1). The parameterized

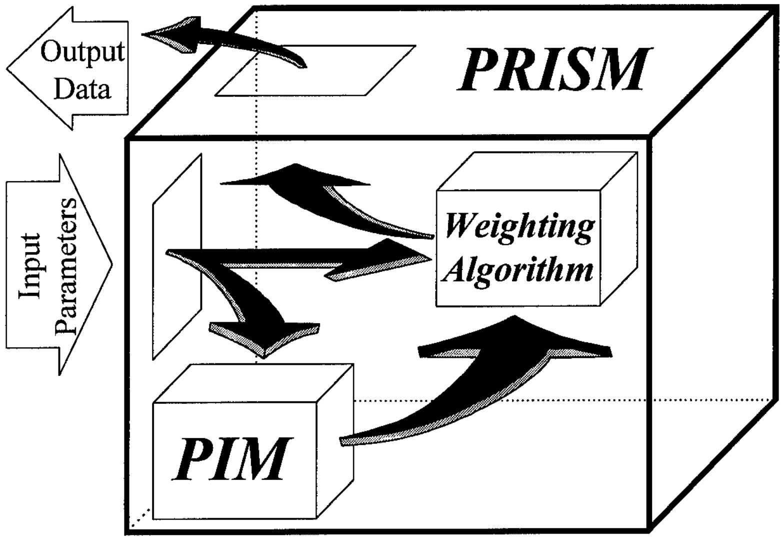

Figure 1. Flow of Data in PRISM

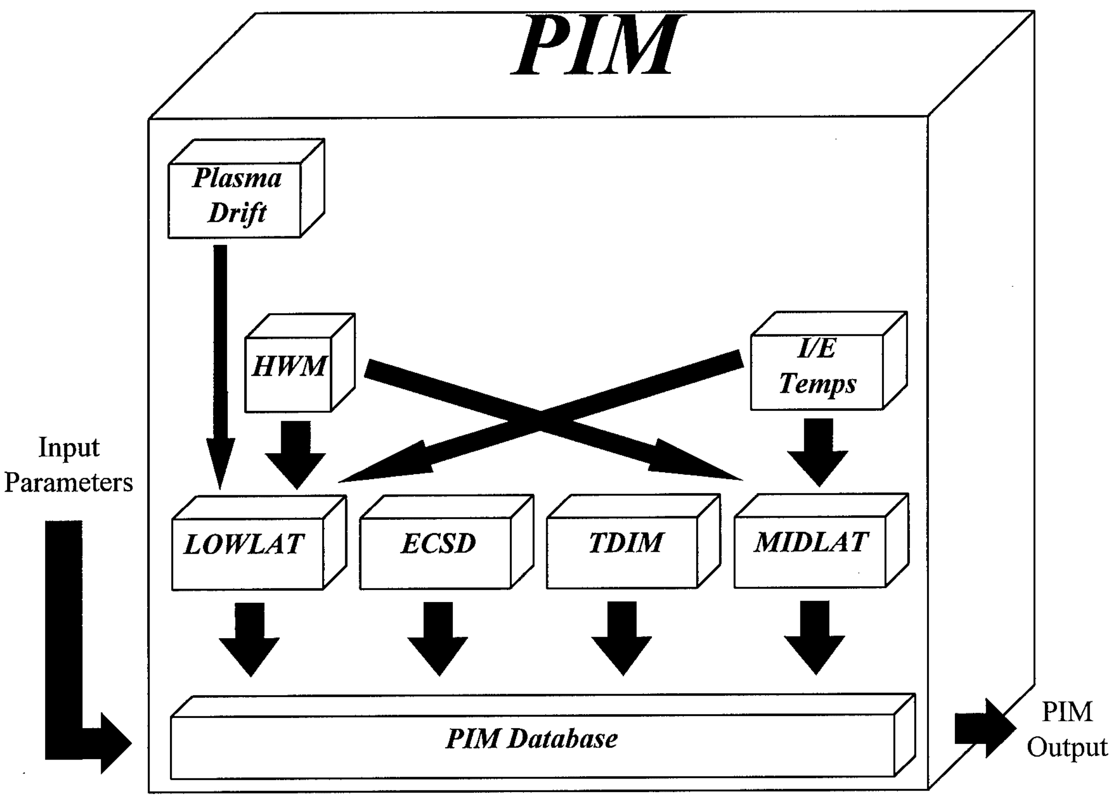

Figure 2. Flow of data in PIM. The component models (plasma drift, HWM, I/E Temperatures, LOWLAT, MIDLAT, ECSD, TDIM and MIDLAT) were run to build the PIM database by CPI. When PRISM is executed, the PIM EOFs provide the ionospheric specification that most closely fits the input parameters.

database was generated using an ensemble of four physics-based ionospheric models and is more commonly known as PIM (Parameterized Ionospheric Model). In addition, information on heat transport, thermospheric winds and plasma drift velocities was used by individual components of PIM. These were provided by a model of ion and electron temperatures developed by *Brace and Theis* [1981], by the Horizontal Wind Model (HWM90) [*Hedin*, 1988] and the *Fejer et al.* [1995] empirical plasma drift data, respectively (see Figure 2).

The four physics-based models used to develop PIM are the Low Latitude F Layer Model (LOWLAT), the Mid-latitude F layer Model (MIDLAT), the combined Low and Mid-latitude E-Layer Model (E region local chemistry code, also designated ECSD) and the High Latitude E and F Layer Model (Time Dependent Ionospheric Model, or TDIM) [*Daniell and Brown*, 1995]. LOWLAT was developed by Dr. Dave Anderson of the USAF Phillips Lab/Ionospheric Effects Branch, Hanscom AFB, MA (PL/GPIM) and was designed to solve the diffusion equation for concentrations of O^+ along a series of magnetic flux tubes in order to develop an altitude profile. In addition to the raw data input into PRISM, LOWLAT makes use of HWM90 winds and ion and electron temperatures from the Brace and Theis model to complete its calculations. The model also considers the equatorial dynamo electric field, which drives horizontal and vertical plasma drifts and so can have a significant impact on output profiles. An adaptation of LOWLAT to midlatitudes is MIDLAT, which was developed by Anderson and modified by Dwight T. Decker. This model is identical to LOWLAT except that there is no longer

a need to consider the equatorial dynamo electric field. Moving to the E layer, ECSD was developed by Decker and John R. Jasperse. ECSD incorporates photoelectrons using the continuous slowing down approximation [*Jasperse*, 1982]. Local photochemical equilibrium is assumed for the calculation of ion concentrations, and the E layer is maintained throughout the night by imposing a small artificial nighttime ion source. Finally, TDIM is used to represent the high latitudes and was developed at Utah State University (USU). There are similarities between LOWLAT, MIDLAT and TDIM. All use flux tubes; however, at high latitudes, the flux tubes must be truncated and a flux boundary condition must be applied at the top. Secondly, the flux tubes move under the influence of the high latitude convection electric field. The effect of horizontal electric fields at low latitudes is to move this ionization vertically, the **E x B** drift direction, since the magnetic field is mainly horizontal. But at high latitudes, the mostly vertical magnetic fields result in horizontal electric fields driving ionization horizontally. Lastly, TDIM also includes an E layer model that incorporates the effects of ionization by precipitating auroral particles [*Daniell and Brown*, 1995]. A more general overview of ionospheric physics pertinent to these models is located in Appendix A.

When the term "model" is used to describe PIM, it should be understood that PIM is actually a parameterized representation of the ionosphere, a theoretical climatological database from which an optimum set of empirical orthonormal functions (EOFs) describing the database was then derived [*Daniell and Brown*, 1995]. The process of building PIM involved running the four component models for different geomagnetic conditions (K_p), solar activity levels ($F_{10.7}$), universal times, Interplanetary Magnetic Field

(IMF) B_y and B_z directions, geomagnetic latitudes and longitudes, and days of the year so that a database of theoretical climatological output could be constructed. It would take a long time and a large amount of computer memory in order to account for every possible combination of the parameters K_p, $F_{10.7}$, UT, etc., so the component models were run for a relatively small number of possible conditions (see Tables 2 and 3). When PRISM is executed in real-time, an appropriate linear combination of the EOFs provides the ionospheric specification (from within the parameterized database) that most closely fits the input parameters. This climatological ionospheric specification is the final PIM output.

Table 2. Geophysical Parameter Values (*Daniell and Brown*, 1995)

Model	Solar Activity, $F_{10.7}$	Magnetic Activity, K_p	IMF B_y Direction	Day of the Year
LOWLAT	70, 130, 210	N/A	N/A	80, 172, 264, 355
MIDLAT	70, 130, 210	1, 3.5, 6	N/A	80, 172, 264, 355
ECSD	70, 130, 210	1, 3.5, 6	N/A	80, 172, 264, 355
TDIM	70, 130, 210	1, 3.5, 6	+, -	80, 172, 264, 355

Table 3. Horizontal Grid Parameters (*Daniell and Brown*, 1995)

Model	Magnetic Latitude	Magnetic Longitude	UT
LOWLAT	-32° to 32° in 2° steps	30°, 149°, 250°, and 329°	MLT: 0.0 to 23.5 in .5 hour steps
MIDLAT	30° to 74° and -30° to -74° in 4° steps	0° to 345° in 15° steps	0100 to 2300 in 2 hour steps
ECSD	-76° to 76° in 4° steps	0° to 345° in 15° steps	0100 to 2300 in 2 hour steps
TDIM	51° to 89° and -51° to -89° in 2° steps	MLT: 0.5 to 23.5 in 1 hour steps	0100 to 2300 in 2 hour steps

1.3 TOPEX Data

The TOPEX mission is a joint endeavor between NASA and the French space agency, Centre National d'Etudes Spatiales (CNES), designed to study the circulation of the world's oceans. This is accomplished through the use of a dual-frequency radar altimetry system which measures the height of sea level. The dual-frequency nature of this radar also allows data on the TEC of the ionosphere to be obtained as a by-product of the measurements [*Fu et al.*, 1994]. The frequencies used are 5.3 and 13.6 GHz. TOPEX records the Differential Phase Delay (DPD) and then reduces this to a measurement of the ionosphere's total (height-integrated) electron density, or TEC (see Appendix B). The TOPEX ionosphere is modeled as a slab at an altitude of 400 km, near the altitude of the F-layer peak electron density [*Imel*, 1994]. *Lanyi and Roth* have estimated the errors in TEC values obtained using this method to be less than 10% [*Lanyi and Roth,* 1988]. For this reason, TOPEX data was chosen as the "ground truth" or control data for this thesis. From this point forward it will be assumed that TOPEX TEC values are representative of the ionosphere.

There is a drawback to using TOPEX TEC values. The TOPEX satellite is designed to operate only over bodies of water. Therefore, there is no TOPEX TEC data available over land. This could present problems since most of the ground stations are located on the mainlands, not on islands, and the number of potential TOPEX TEC observations taken near a ground station is greatly reduced. This constraint on the ground truth data might introduce some error, although this impact is expected to be small. A

second drawback is that the TOPEX TEC data is not available at high latitudes, requiring that this validation be restricted to low- and mid-latitudes.

1.4 Input and Output Data Parameters

As mentioned earlier, PRISM consists of two primary components: the weighting algorithm (or Real Time Adjustment algorithm) and PIM. Each of these components ingests different parts of the input data package (see Figure 3). PIM needs information on solar activity ($F_{10.7}$, both daily and 90-day average), magnetic activity (K_P), and the direction of the IMF B_y (east or west) and B_z (south or north). PIM then uses these indices to construct, using the PIM EOFs, the "best fit" representation of the ionosphere to be found within the PIM database (created from the output of the four physics-based models that make up PIM). The PIM output is then fed into the Real Time Adjustment (RTA) algorithm along with the model-run-time observational input data from DMSP, IMS and DISS. How the RTA combines PIM output with the remaining input data package is discussed in *Noted Discrepancies in PRISM Output Data* below.

PRISM output can be produced in two different formats. The user can choose between a global or regional latitude/longitude grid (in geomagnetic or geographic coordinates) or a set of user-specified points (for example, a satellite orbital path). Once the format is chosen, the user can specify which parameters to output. The possible output parameters include vertical electron density profiles, critical frequencies (for E and F_2 layers), layer peak heights (for E and F_2), and vertical TEC [*Daniell et al.*, 1995].

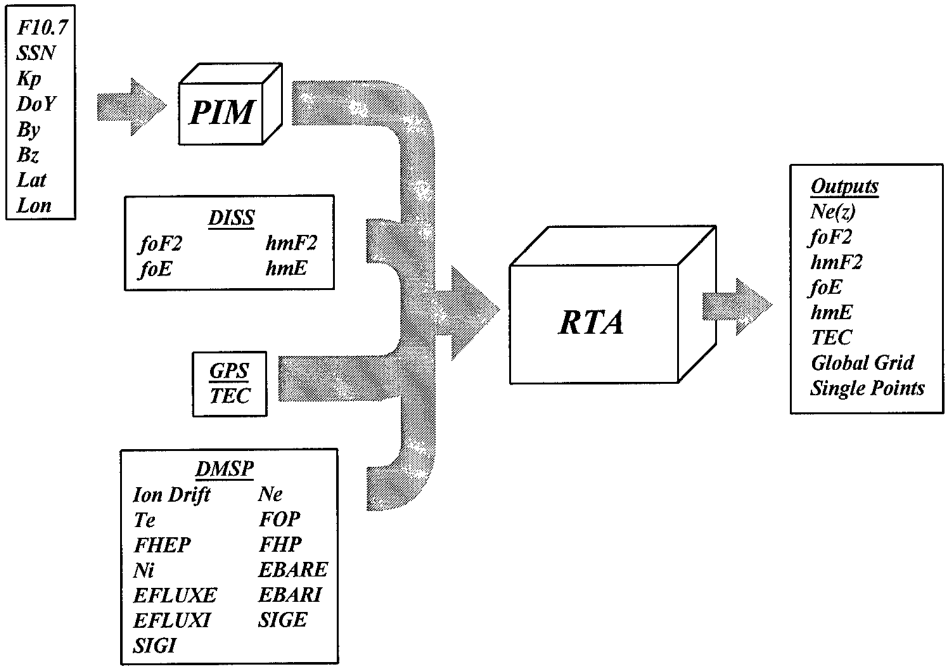

Figure 3. PRISM Inputs and Outputs. Terms are defined in Appendix H.

1.5 Noted Discrepancies in PRISM Output Data

One result of the earlier validation of PRISM was the addition of a new RTA algorithm to replace an algorithm based on least-squares fitting of a ten-parameter function of latitude and longitude. This new algorithm is based on a weighted mean of the PIM output plus the real-time input data designed so that PRISM's specification will match the input data at the precise location at which the input data was obtained. This new algorithm is also responsible for several reported PRISM output errors associated with (1) the geographic boundaries of the PIM component models as represented in the PIM database and (2) large differences between PIM output and real-time station input data at a particular location. The PIM database must merge the output from the four models in order to produce a global specification of the ionosphere. LOWLAT and

MIDLAT merge near 30° latitude, and MIDLAT and ECSD merge with TDIM near 60° latitude. At the boundaries where this merging occurs (usually done over a 4-8 degree wide latitudinal zone) a weighted average is taken of the values from two models. The weight shift starts at the southern boundary of the zone with 100% of the lower latitudinal model contributing to the database output. As the PIM database moves poleward in this merging of model output data, it gradually decreases the influence of the lower latitudinal model and increases the impact of the higher latitudinal model until the higher latitudinal model contributes exclusively to the final PIM output (See Figure 4). The problem results when there is a large difference between the overlapping values of the two models. The PIM database merges this data over a relatively short latitudinal range, and a steep horizontal gradient can become apparent. Next, the RTA combines real-time observed data with the merged-model theoretical climatological output from PIM. An unfortunate consequence of this method of combining theoretical climatology with real-time observations is that if, at a particular observation location, the observed data differs